NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-791

System Design for a Nuclear Electric Spacecraft Utilizing Out-of-Core Thermionic Conversion

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PREFACE

The work described in this report was performed by the Propulsion Division of Jet Propulsion Laboratory.

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ABSTRACT

A nuclear power system under investigation at the Jet Propulsion Laboratory utilizes heat pipes to transport thermal power from a fast spectrum nuclear reactor to a thermionic converter array. Conversion of nuclear thermal power to electric power in quantities large enough to provide primary propulsion is of interest for advanced spacecraft. This effort at JPL with the cooperation of the Los Alamos Scientific Laboratory is directed toward determining the feasibility of a heat pipe reactor concept to transfer heat to out-of-core thermionics as an alternate to the in-core thermionics concept previously investigated by Gulf General Atomics. The principal advantage of this approach is to eliminate nuclear fuel burn-up interactions with the thermionic converters and also allow the thermionics to be removed from the hostile environment of the reactor.

The space shuttle, under current development, would be used as the primary launch vehicle for this nuclear electric spacecraft; thus the shuttle payload bay constraints dictate physical dimensions, layout configuration, maximum weight, and permissible center of gravity. Power levels between 400 kW and 1 MW would be required to perform far outer planet missions within a reasonable time frame. A 400-kWe power level system which would have a specific weight ≤20 kg/kW was selected for this study, because this size appears to be the largest (in both volume and weight) that is compatible with the shuttle payload bay, thus utilizing a single launch for a spacecraft that can accomplish the greatest number of missions.

This technical memorandum addresses the basic guidelines for the nuclear reactor, heat pipes, thermionic converters, shields (neutron and gamma), waste heat rejection system, and the electrical bus bar-cable system required to transport the high current/low voltage power to the processing equipment.

I. INTRODUCTION

Mission studies have established the need for Advanced Propulsion Systems if far outer planet explorations are to be accomplished within a reasonable time frame (Ref. 1). Conclusions from previous studies by NASA and the Atomic Energy Commission (AEC, now ERDA) are that the ability to economically explore the far outer planets in any detail is predicated upon the development of low-cost high-power lightweight power sources that are independent of solar energy. The advanced propulsion comparison (APC) studies show nuclear electric propulsion (NEP) as a potentially versatile economical candidate for this role, based on the assumption that the needed long life and high reliability can be obtained using thermionic conversion of nuclear thermal to electrical energy (Ref. 2). Previous NEP work utilized high temperature (~1900°K) in-core thermionic conversion systems (Ref. 3). These systems appeared to have lifetimes limited to 10,000 to 20,000 full power hours inasmuch as the thermionic converter electrodes were subjected to physical damage by nuclear fuel swelling and were degraded by nuclear fuel diffusion. The high reliability requirement was jeopardized by a potential "single point" failure in the coolant system, since a single coolant loop was provided for all converters. In addition, the technology program was indicating problems that would force the specific weight for this in-core power subsystem into the 30 to 40 kg/kW range. This high weight rendered it less desirable for many deep space missions.

By removing the thermionic converters and related hardware from the reactor assembly (the out-of-core concept) and utilizing heat pipes to thermally couple the nuclear reactor with the thermionic converters, the many lifetime limiting problems of the in-core concept are apparently eliminated. The predicted lifetime can conceivably be extended up to 70,000 hours because out-of-core converters are not subjected to the hostile environment of nuclear fuel contamination and physical damage imposed on the electrodes by nuclear fuel swelling. High reliability is obtainable through full modular redundancy of all the systems that have been incorporated in the design to eliminate single-point failure. An additional advantage is that less complex fabrication procedures can be utilized, since individual thermionic converters can be assembled and tested independently of the reactor system.

Advanced technical studies for the development of NEP were initiated at JPL during FY 1975, (Ref. 4). These studies revealed that with the out-of-core concept a more compact reactor could be designed with a power subsystem specific weight that could approach 20 kg/kW. A specific weight of this order is dependent on improvements in the thermionic converters that would be required to have a barrier index of 1.6 eV (collector work function 1.5 eV and plasma arc drop of 0.1 eV). Recent work has indicated that these improvements can be realized in the near future (Ref. 5). The required barrier index will, in turn, theoretically provide converter efficiency on the order of 15% with emitter and collector temperatures of ~1650 and ~950 K, respectively. At this lower temperature the emitter and heat pipe components can be fabricated from molybdenum instead of the tungsten needed for the in-core emitter components that were supplied heat at ~1900 K (Ref. 3). Tungsten is heavy, expensive, brittle at room temperature, difficult to fabricate, and does not join well with any other material. In comparison to tungsten, molybdenum weighs ~50% less, costs ~75% less, and is much easier to fabricate and join with other materials.

This technical memorandum describes some of the mechanical design parameters for a nuclear-powered spacecraft system that have been developed during a current investigation at JPL, conducted with the cooperation of the Los Alamos Scientific Laboratory (LASL).

II. NEP SPACECRAFT

A conceptual drawing of a nuclear electric powered spacecraft is shown in Fig. 1. The nuclear reactor and the thermionic converter subassembly are located at the extreme right aft end of the vehicle. The next component forward of the reactor/converter assembly is the shadow shield, which is configured to provide a 23-deg cone angle of radiation protection to the spacecraft and which is comprised of two major subassemblies. The right-hand subassembly is a neutron shield fabricated from lithium hydride (LiH). The remaining portion is the gamma shield, which is mercury propellant in a suitable enclosure. Because the LiH shield material will dissociate, a radiator designed to reduce the LiH shield temperature is mounted between the main support boom and the

surface supports which also serve as electrical bus bar troughs. The coolant plumbing is routed from the thermionic converters to the main high-temperature radiator, passing over the shields in a biased configuration to minimize neutron streaming. This coolant plumbing is then routed through the hollow main support boom. The high-temperature radiator is a full spacecraft diameter, as shown in Fig. 1, and is located behind an ion thruster assembly. The NaK-78 liquid metal (LM) coolant is circulated through the multichannel system (radiator and thermionics) by a multiduct electromagnetic (EM) pump located inside the radiator shell. The ion thrusters are canted out at a 9-deg angle to reduce exhaust impingement on other spacecraft surfaces. Those surfaces are also covered with a sputter-resistant coating (possibly Kapton). The power conditioner and its radiator shown to the left of the main radiator was deployed from its stowed position inside this main radiator. The science payload package shown at the left end of the spacecraft was in turn deployed from the shell-type power conditioner/radiator assembly. The science antenna was deployed from the science package and remains within the 11.8-m-diam protective shield cone.

III. DESIGN PARAMETERS

A. SHUTTLE CONSTRAINTS

The shuttle under current development would be used as the primary launch vehicle for a nuclear electric spacecraft, and thus the shuttle payload bay constraints dictate physical dimensions, layout configuration, maximum weight, and permissible center of gravity. Based on the Advanced Planetary Mission Committee study, it appeared that power levels between 400 kW and 1 MW would be most desirable to perform large payload outer planet missions within a reasonable time frame (Ref. 6). A system with 400 kWe available for thrust was selected for this study because the volume and weight appear to be compatible with the shuttle payload bay constraints. This power level provides multimission capability with economical single-shuttle launches. Higher power-levels may require two shuttle launches and space assembly or a heavy lift launch vehicle.

B. PROPULSION SYSTEM

Of prime importance is a space propulsion system which allows maximum utilization of the spacecraft and provides multimission flexibility. These requirements can be accomplished by providing an unemcumbered end portion of the spacecraft without thermal sources that would provide greatest flexibility for the various science gathering payload packages. To provide a spacecraft with maximum payload and maximum payload versatility the propulsion system must be designed for minimum physical size and mass. To comply with this requirement the nuclear reactor and thermionic conversion components were configured through parametric evaluations with optimum parameters being selected for minimum weight. This effort is discussed in detail in Refs. 7 and 8.

1. Reactor/Thermionics Heat Pipes and Radiation Shield

Nuclear radiation shields contribute significantly to the power system mass and, therefore, must be located so that the least material provides the most shielding. With the shields properly dimensioned and located adjacent to the nuclear reactor/thermionic converter assembly a shadow cone is provided that can shield the sensitive electronic components. The neutron shield was designed to limit the dose level to 10^{12} nvt ($E_n \geq 1.0$ Mev) at the deployed power processor ~17 m from the nuclear reactor. For this 400-kWe design the LiH neutron shield weighs ~2000 kg, which is ~25% of the power system mass. The gamma shield limits the dose level at the deployed power processor to 10^6 rads. Mercury propellant in excess of that required to accomplish the mission is provided to assure the required dose level protection until completion of science gathering.

A more detailed view of the interfaces between the major components of the out-of-core (nuclear reactor — thermionic conversion) power plant concept is shown in Fig. 3. The heat pipe is the "heart" of this out-of-core concept. As depicted in this center view, the nuclear fuel element of UO_2 in molybdenum is nickel activated diffusion bonded to one end of the molybdenum heat pipe. This interface is sized so that the thermal transfer requirement does not exceed 100 W/cm^2 for the fuel/heat pipe contact area. Also the heat pipe is sized so that the heat flux to be transported does not exceed 10 kW/cm^2 of

vapor cross section area (15 kW/cm^2 has been demonstrated) (Ref. 9). Six thermionic converters are electrically insulated from and mounted on each heat pipe forward of the fuel.

The converter in the left view of Fig. 3 is cut away to show the layout of the various components around the heat pipe. Converter buildup will first require an insulator applied to a heat pipe. The remaining converter elements shown in this figure are the emitter, interelectrode space, collector, collector insulator and coolant passage. Spacers are required to maintain a uniform interelectrode gap. End seals and the cesium system plumbing details remain to be developed. The right-hand view of Fig. 3 shows the powerplant assembled with most of the hardware present. Components such as the support structure, control drum actuators, and the cesium system have been omitted. This out-of-core concept will simplify fabrication procedures, because the nuclear fuel and thermionic converter subassembly components can be fabricated, assembled, and tested simultaneously and independently of each other. This was not the case for the Gulf General Atomic (GGA) in-core design (Ref. 3).

The 400-kWe out-of-core thermionic reactor (Figs. 2 and 3) is approximately 2 m long by 0.82 m in diameter. Compared to the 120-kWe GGA in-core reactor (Ref. 3) (0.925 m long × 0.737 m in diameter) this out-of-core system provides almost four times the power for up to seven times the full power hours and is only about twice as large.

2. Electrical Connections

A cross section through the thermionic converters is shown in Fig. 4 with minimum detail. This arrangement is hexagonal to provide a uniform pattern for electrical bus bar connections and an electrically balanced system. The center heat pipe assembly was omitted for electrical symmetry and nuclear fuel power flattening. Higher temperatures are experienced in the center of a fuel pile with a temperature gradient radially to the reactor perimeter. Removing fuel from the center and adding fuel to the perimeter minimizes this temperature gradient. For electrical connections, the internal bus bars are molybdenum and the external bus bars are copper. These selections are based on material property compatibility with the environment and on space allocation.

As noted in Fig. 4 each layer of thermionic converters is separated into three modules each containing thirty converters. Connections are made in a series-parallel manner as shown schematically in Fig. 5. This connection scheme is intended to provide redundant reliability in the event of a converter failure. For example, in the event of a heat pipe failure, one of the 30 converters in each of six series-parallel connected modules would become inoperative, probably in an electrically open-circuit mode. System power would be shunted around the inoperative converter units with a total power loss of ~1%. This reliability through redundancy is also provided at the nuclear fuel/heat pipe interface. The reactor cooling scheme utilizing heat pipes is easily arranged so that each nuclear fuel element is cooled by several heat pipes. Thus, if one heat pipe fails, its heat-transfer load is shared by the adjacent heat pipes (Fig. 6). With the thermionic system operating at full power (~36 kWt/heat pipe), each heat pipe is transporting ~7.26 kWt/cm^2 of its vapor cross section area. The most severe condition occurs when there are only two adjacent pipes to share the load from an inoperative heat pipe. There are only six of these heat pipes in the system at the corners of the reactor. In this case the final loading on these two heat pipes that share the load would be <75% of their capability (Ref. 9). Out-of-core converters are not subjected to as hostile an environment of nuclear fuel swelling as was the case for the GGA in-core design (Ref. 3).

With these lifetime limiting problems eliminated, this out-of-core power system has the potential of being able to operate at full power for ~70,000 hours. The UO_2 fuel pellets loaded in a molybdenum matrix, based on calculations for fuel swelling and burnup, will be capable of providing the required thermal power for this 70,000 hours. The reactor design will permit the expected 1% fuel volume swelling (Ref. 7). The limiting factor is expected to be lack of control margin produced by the control drums. These converters are fabricated in 15-cm lengths for two reasons. First, the amount of electrical current which can be generated by and extracted from a cylindrical thermionic converter is limited by a tradeoff between the volume of electrode material (thickness and length) versus an acceptable value of I^2R loss during this electrical power extraction. Second, the converter units must be electrically connected in series as a voltage-increasing mechanism which is needed to reduce

the mass of the low-voltage cables and increase the efficiency of the power processor. (For a fixed power level, an increase in voltage permits a decrease in current, and thus smaller cross-sectional area cables can be used between the converters and the power processor. Also power processors are less complex and more efficient when input power is supplied at voltages ≥15.)

A thermal flux input temperature ≤1650 K to the thermionic permits emitters, heat pipes, and system internal electrical power extraction bus bars to be fabricated from molybdenum instead of tungsten which was required to withstand the higher temperature of ~1900 K used in the GGA in-core design (Ref. 3).

Figure 7 shows the series connections which are made with molybdenum links mounted on each end of each converter. These links are designed with a tension finger arrangement to provide proper alignment during heatup expansion. These bus bar links are designed so that when installed, the parallel electrical paths are established by an interlocking physical contact with the adjacent row of links. The cross-sectional areas of these links are such that the voltage drop will be less than 2% during full-power operation with a mean temperature of ~1100 K within the link. A thermal choke (an area of reduced cross section) is provided at each end of each converter emitter which limits thermal conduction through the series connection links without imposing a significant increase in voltage drop.

As previously stated and shown in Figs. 3 and 4, this nuclear reactor/thermionic converter powerplant is divided in thirds for electrical connection symmetry. Figure 8 shows the method employed to electrically connect the eighteen modules in series. The electrical paths through each module are shown schematically with arrows. The system modules and thirds are spread out to more readily display the connection scheme. The converter module layers are mounted on the heat pipes with a 30-mm space allowance on each end for electrical connections. The system thirds are separated by 20-mm gaps to provide space for the series connection molybdenum bus bars, loaded <150 A/cm^2, which complete the electrical circuit between modules. The system thirds are electrically connected in series with copper bus bars or cables sized to carry approximately 275 A/cm^2 that are mounted around the

outside perimeter of the system. The aluminum cables from the powerplant to the power processor carry ~174 A/cm^2. I^2R loss incurred during transport of the power from the converter terminals to the power processor is ~11.3% of converter terminal power. Design parameters for the electrical system are recorded in Table 1. The mass breakout for the power system as currently configured is shown in Table 2. The specific mass is ~21 kg/kW, which is slightly above the desired goal.

3. Ion Thrusters

The shield shadow cone (Fig. 2) is 4.5 m in diameter (full spacecraft diameter) at 9 m from the aft end of the nuclear reactor. All thrusters are located within the shield cone shadow to minimize scatter of radiation with subsequent operational impairment of sensitive electronic components such as the thruster power processor. The ion thrusters are canted at 9 deg to minimize thruster material impingement on other components. This canted attitude results in a 1% loss in effective thrust (Ref. 10). However, canting does not fully eliminate back-sputtered material that could impair thruster operation. As stated in Section II, the support boom, the electrical cable channels, the electrical cables and the low-temperature LiH shield radiator will be protected from thruster exhaust impingement with a thick coating of Kapton or similar sputter-resistant material in order to reduce the quantities of back-sputtered material to an acceptable level.

4. High-Temperature Radiator

The high-temperature radiator removes the excess heat from the thermionic converters and contains ~1000 heat pipes utilizing potassium (K) working fluid.

This radiator is fabricated from niobium (Nb), has an outer layer ~2.1 mm thick of beryllium (Be) for meteoroid protection, has an iron titinate coating for high thermal emissivity and is located behind the thrusters for the following reasons:

(1) To utilize full spacecraft diameter to provide the required radiation surface area with a minimum length assembly.

(2) To eliminate damage to the required high emissivity coating from thruster material impingement.

(3) To provide an enclosure for the electromagnetic (EM) pump which circulates the NaK-78 liquid metal (LM) coolant. (The plumbing for this system passes through the support boom and therefore mounting the EM pump inside the radiator provides a straight through plumbing path.)

(4) This shell-type radiator assembly easily adapts as a stow area for other components such as the power processor and the science packages (payload) which are deployed in space.

The coolant passages around each converter will be ganged in the manifold configuration shown in Fig. 9. To maintain the required redundancy for reliability, eighteen individual coolant loops are provided. To insure that impaired coolant flow in one loop does not jeopardize the entire powerplant, these coolant manifolds are ganged with the series electrical connection pattern, and thus a single coolant loop failure will not initiate an electrical malfunction with a resultant electrically open-circuited system. The converter conversion efficiency determines the percentage of thermal power that must be removed from the thermionic converter and radiated to space. A 500-kWe gross system with a conversion efficiency of 15% would require a 3.33 MWt gross system source of which 2.83 MWt would be radiated to space. The space shuttle bay size and other constraints of the spacecraft concept place maximum dimensional limits on the radiator of 9 m in length and 4.5 m in diameter. The required radiator area is inversely proportional to the fourth power of the rejection temperature. Thus the temperature of the rejected thermal power must be high enough to allow for an acceptable radiator size. More details for this design based on thermionic converter design parameters are provided in Ref. 8.

5. Thermionic Conversion System Parameters

The thermionic conversion system parameters determined during this design study are listed in Table 3. Barrier index, a thermionic converter characteristic which opposes electrical output, is the sum of collector work function (ϕ_c) and plasma arc drop (V_d). These parameters are measured in

electron volts. Converter performance curves (efficiency versus collector temperature) have been plotted for barrier indexes of 1.6 and 1.8 eV as shown in Fig. 10. Other fixed parameters used in calculating these curves are also shown in Fig. 10. The curve for 1.6-eV barrier index composed of 1.5-eV collector work function and 0.1-eV plasma arc drop provides ~15% converter efficiency with a collector temperature of ~950 K. These parameters, which represent a slight improvement over demonstrated converter performance [existing laboratory devices have operated with a barrier index of 1.8 eV] (Ref. 5), are needed for design of a spacecraft with 400 kWe available for thrust (multimission capability) sized for an economical single-shuttle launch.

IV. CONCLUSIONS

This initial investigation into the out-of-core nuclear/thermionic power system has revealed the following advantages as compared to the in-core system extrapolated to the same power level:

(1) A single-shuttle launch will provide more power on station, inasmuch as a smaller power source can be designed utilizing the heat pipe cooled reactor with out-of-core thermionics. This smaller nuclear reactor/thermionic conversion system, in turn, scales down other components, such as the nuclear radiation shield (a significant portion of the power system mass) and makes feasible a power subsystem with a specific weight on the order of 20 kg/kWe.

(2) The predicted lifetime for the thermionics can conceivably be extended by up to a factor of ten, when partially removed from the hostile nuclear fuel environment (fission product contamination and particularly fuel swelling).

(3) High reliability can be attained through a modularly redundant system that fully eliminates the otherwise possible single-point failure. This inherent reliability of the thermionic power conversion system is one of its major features.

(4) The selection of more fabricable materials (molybdenum in lieu of tungsten for the emitter and heat pipes) is permitted by the lower operating temperature ~1650 K instead of ~1900 K.

(5) A less complex fabrication procedure can be utilized, since the individual thermionic converters can be assembled and tested simultaneously and independently of the reactor system.

REFERENCES

1. Outlook for Space Reference Volume, A Forecast of Space Technology, 1980-2000, National Aeronautics and Space Administration, Washington, D.C., July 15, 1975.

2. Advanced Propulsion Comparison Study, edited by I. L. Helms, Space Nuclear Systems Division of USAEC and NASA, Washington, D.C., April 1, 1973.

3. Development of a Thermionic Space Power System, Final Summary Report, Gulf General Atomic Report, GA-A12608, June 30, 1973.

4. Estabrook, W. C., Koenig, D. R., and Prickett, W. Z., Comparative Assessment of Out-of-Core Nuclear Thermionic Power Systems, Technical Memorandum 33-749, Jet Propulsion Laboratory, Pasadena, Calif., November 1975.

5. Private communication from E. Britt, Rasor Associates, Inc., Sunnyvale, Calif., January 1976.

6. The 1973 NASA Payload Model — Space Opportunities, National Aeronautics and Space Administration, Washington, D.C., October 1973.

7. Koenig, D. R., Heat Pipe Nuclear Reactor for Space Power, to be presented at the 11th Intersociety Conference, Stateline, Nev., September 1976.

8. Phillips, W. M., Hsieh, T., and Estabrook, W. C., Nuclear Thermionic Power System for Spacecraft, to be presented at the 11th Intersociety Conference, Stateline, Nev., September 1976.

9. Vinz, P., and Busse, C. A., "Axial Heat Transfer Limit of Cylindrical Sodium Heat Pipes Between 25 W/cm^2 and 15.5 kW/cm^2," Proceedings of the First International Heat Pipe Conference, Stuttgart, Germany, 1973.

10. Nuclear Electric Propulsion Mission Engineering Study, General Electric Co., Document No. 73SD 4219, published by General Electric Space Division, Valley Forge, Pa., March 1973.

Table 1. Design parameters for electrical system

	Material	Conductor length,[a] cm	Area, cm^2	Load amperes	Current density, A/cm^2	Mean[b] temperature, °K	I^2R loss, %	Total[c] component weight, kg
Main links	Mo	13	5.4	745	138	1100	1.24	315.7
End links	Mo	5.25	5.07	745	147	1100	0.43	59.8
Inside plates	Mo	40/4	31	4470	144	1100	4.41	125.5
Subtotal (molybdenum)							6.08	501.0
Outside plates	Cu	40/4	31	4470	144	700	0.95	121.3
Outside jumpers	Cu	65	32.5	8940	275	700	0.30	37.6
Cables to power processors	Al	3200	51.4	8940	174	400	3.99	444.1
Subtotal (copper and aluminum)							5.24	603.0
Total							11.3	1104.0

[a] Electrical current path length.
[b] Predicted conductor operating temperature used in I^2R loss calculation.
[c] Weight for component in 540 converter (527 kWe gross) system.

Table 2. Component mass

Component	Weight, kg
Reactor core (L/D = 1)	932
Reactor reflectors and control	773
LiH shield	2030
Heat pipes	364
Thermionic converters	805
Molybdenum bus bars	501
Copper bus bars	159
Aluminum cables to power processor	444
Coolant plumbing	430
Coolant (NaK 78)	498
EM pumps	~200
Primary radiator	793
Support structure (5%)	400
Total mass, kg	8329
kg/kWe (400-kWe system)	20.82

Table 3. Thermionic conversion system parameters — 90 heat pipes, 5.4 kWe/heat pipe

Number of converters	540
Converter barrier index	1.6 eV
Converter ϕ_c	1.5 eV
Converter V_d	0.1 eV
Percent of converter efficiency η	15
Converter emitter power density	6.0 W/cm^2
Converter volts at 10 A/cm^2	0.6 V
Emitter area/converter[a]	176.7 cm^2
Collector area/converter[a]	193.5 cm^2
Converter length	150.0 mm
Heat pipe OD	28.0 mm
Heat pipe length	1920 mm
Emitter diameter	37.5 mm
Reactor diameter	621 mm
Reactor length including reflector	760 mm
Overall length — reactor and heat pipes	2020 mm
Emitter temperature T_E	1650 K
Collector temperature T_c	950 K
Radiator temperature mean T_R	925 K
Radiator area[b]	82 m^2
Radiator length at 4.5 m dia.[b]	5.8 m
Gross output (BOL)	9760 A
Gross output (BOL)	54 V
Gross output (BOL)	527 kWe
Nominai operating power	483 kWe
Rejected power	2737 kWt
Reactor thermal power	3220 kWt
LiH shield	2030 kg

11.3 cable losses — 55 kW = 472 kWe
28 kW for coolant pumps and hotel power = 444 kWe
10% degradation during lifetime yields 400 kWe (EOL) input to thrust system

[a]Includes ~8.7% excess area for converter end thermal degradation
[b]Contains 10% safety margin
BOL = beginning of life; EOL = end of life

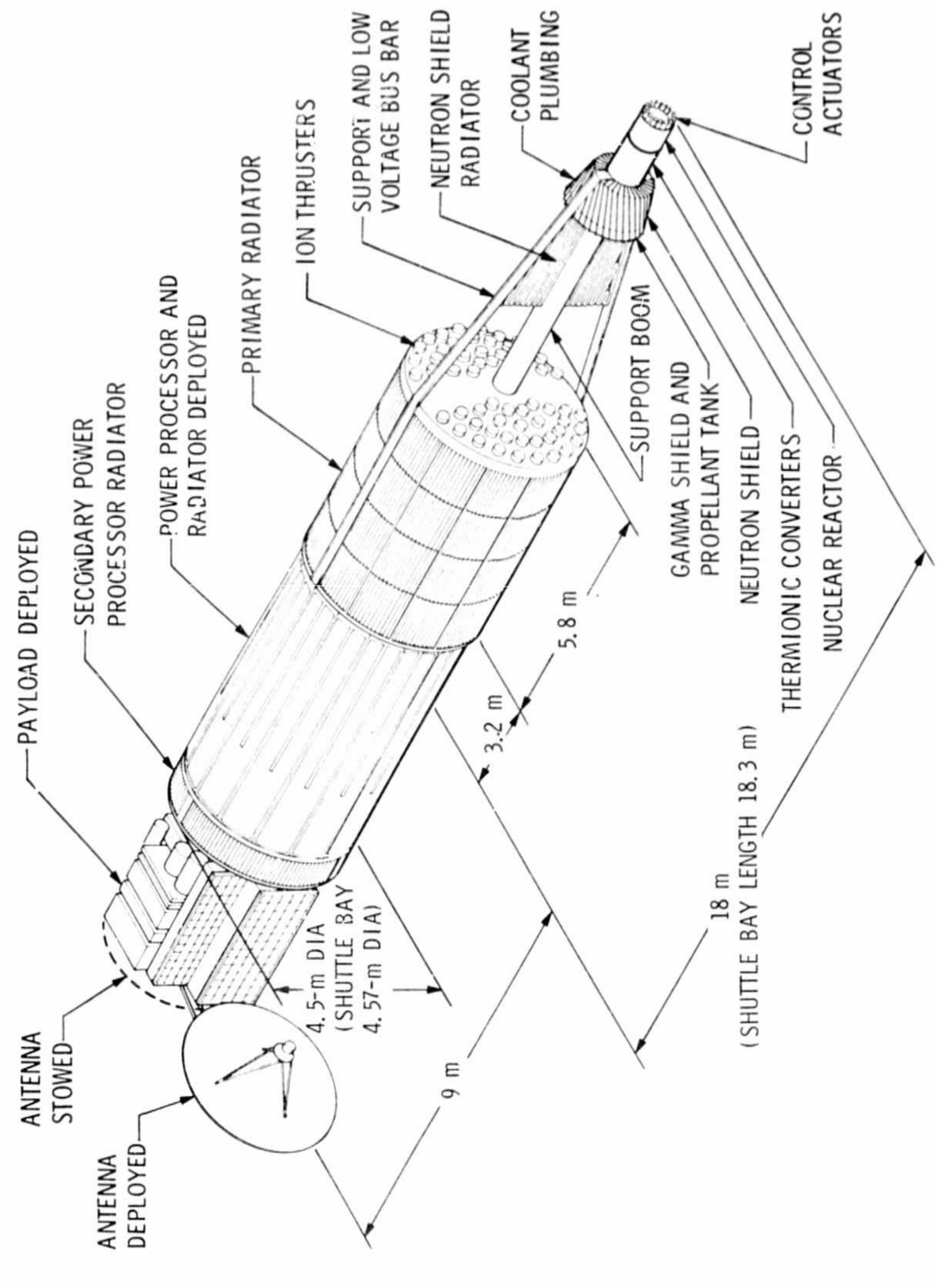

Fig. 1. NEP spacecraft with thermionic conversion—deployed configuration

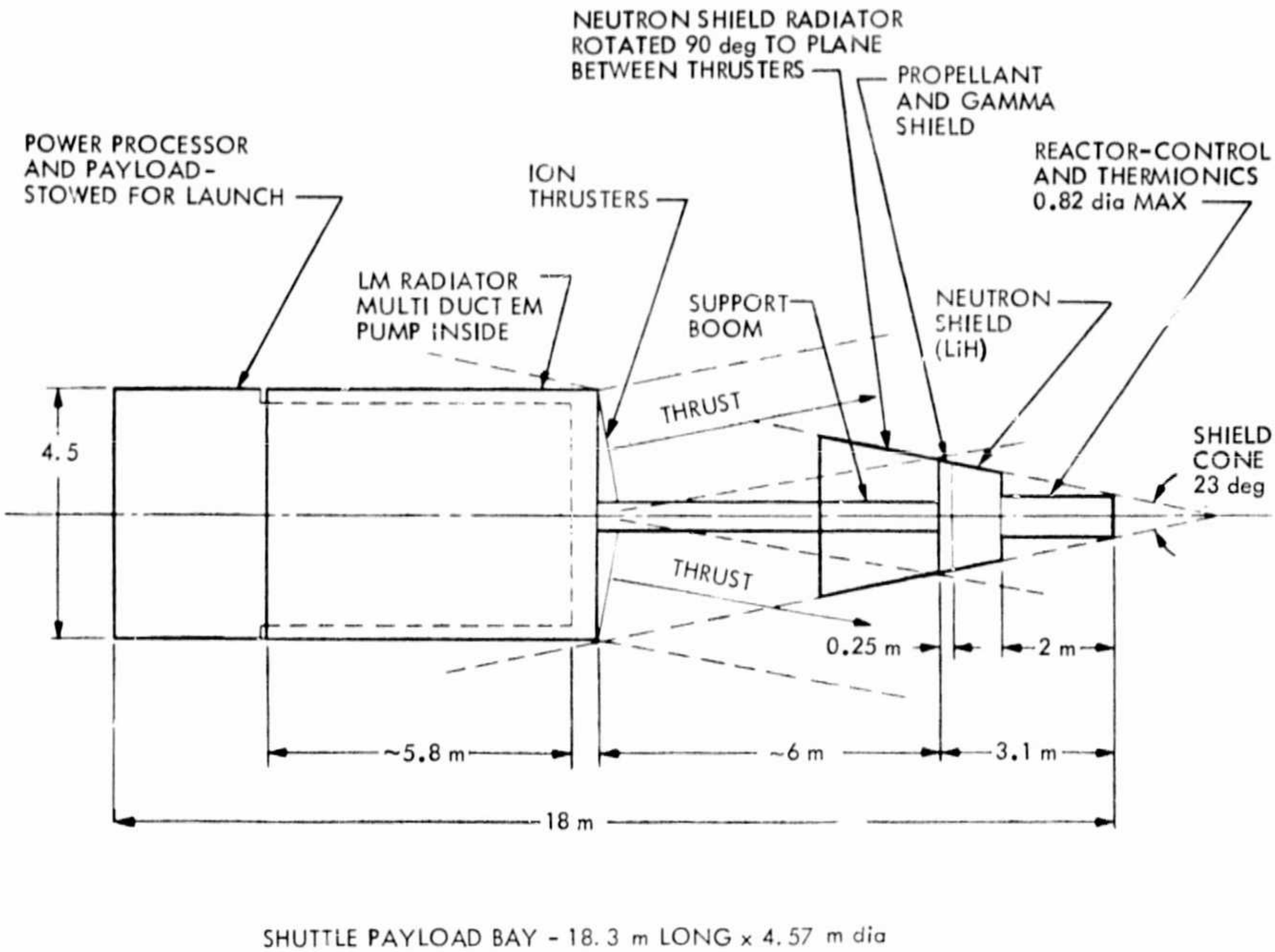

Fig. 2. Proposed nuclear electric propulsion end thrust spacecraft configuration

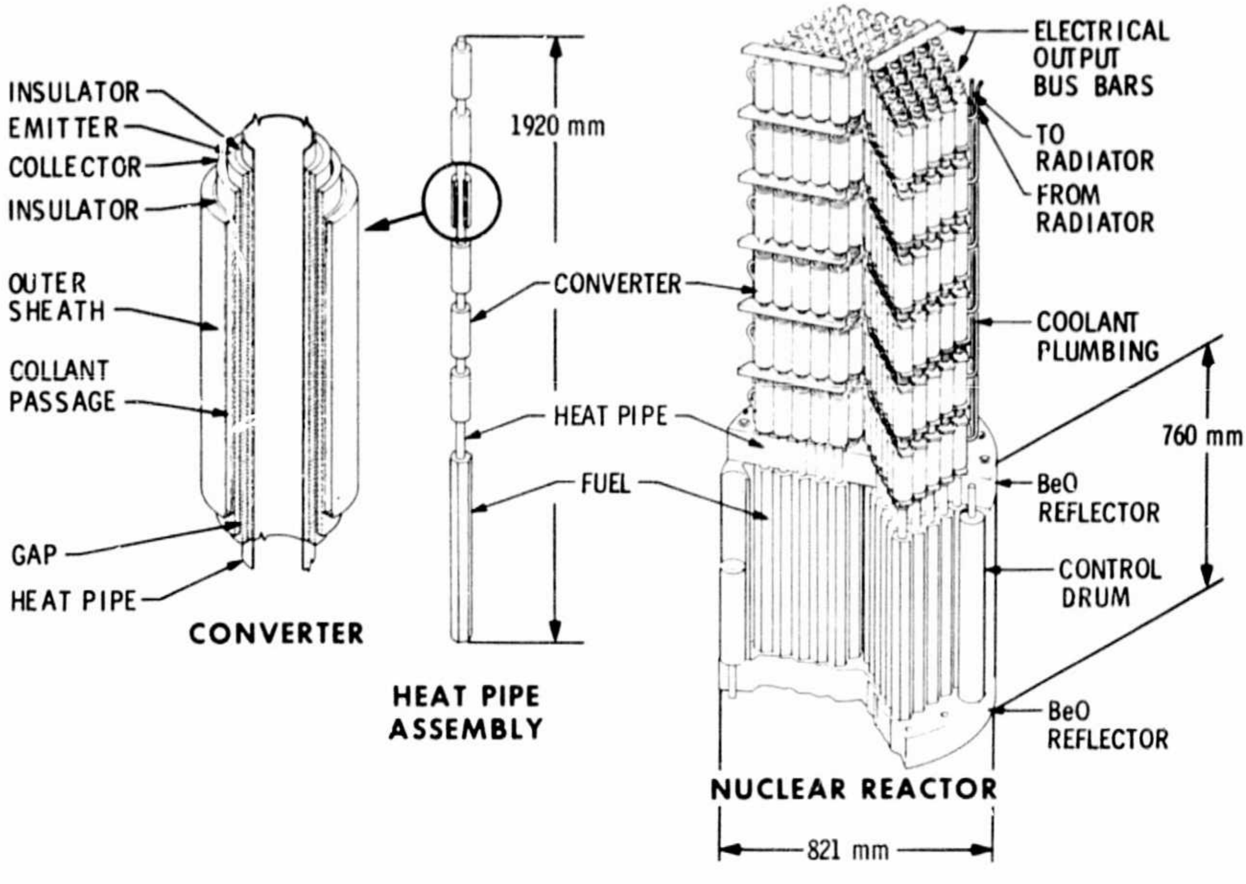

Fig. 3. Out-of-core thermionic reactor concept

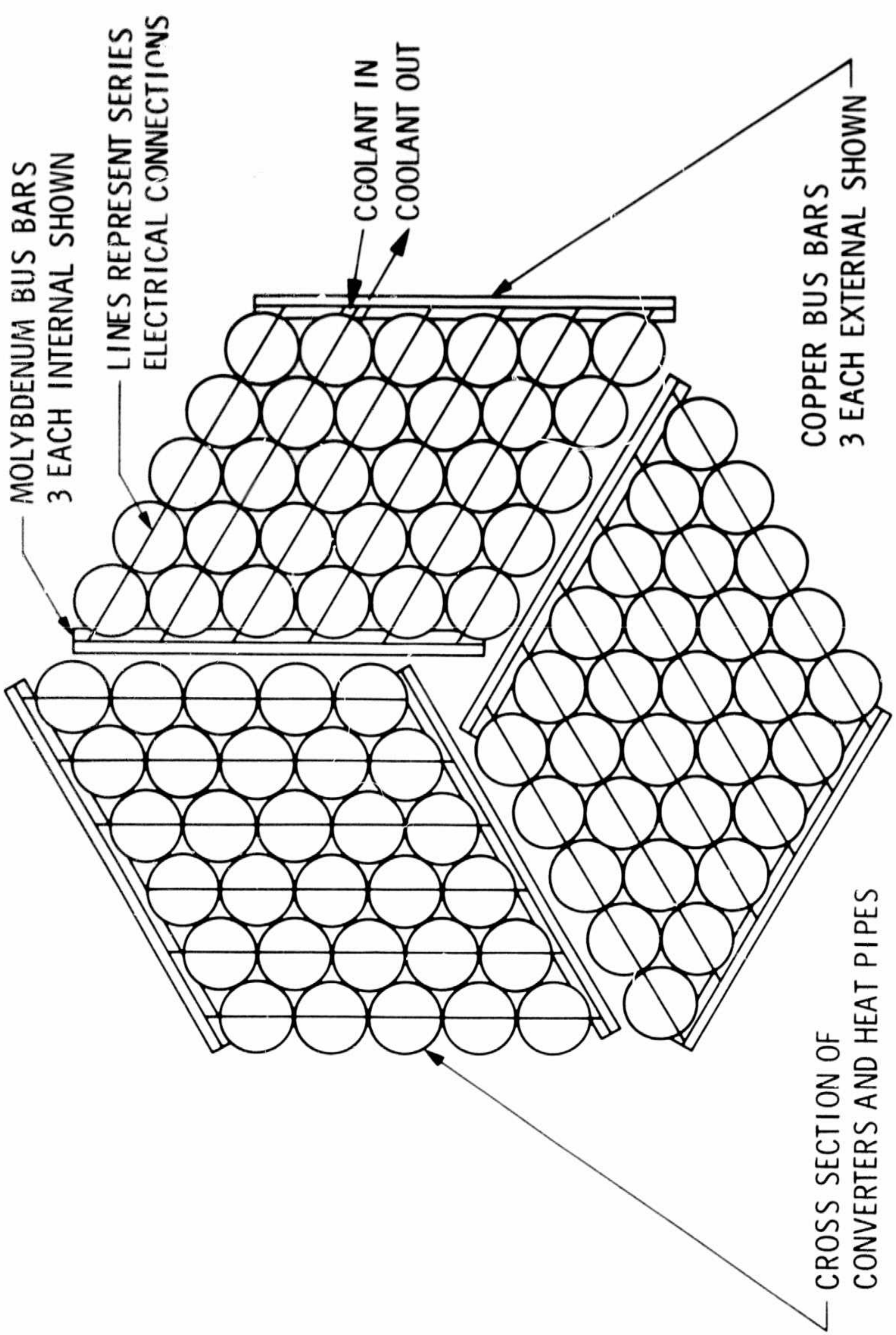

Fig. 4. System cross section

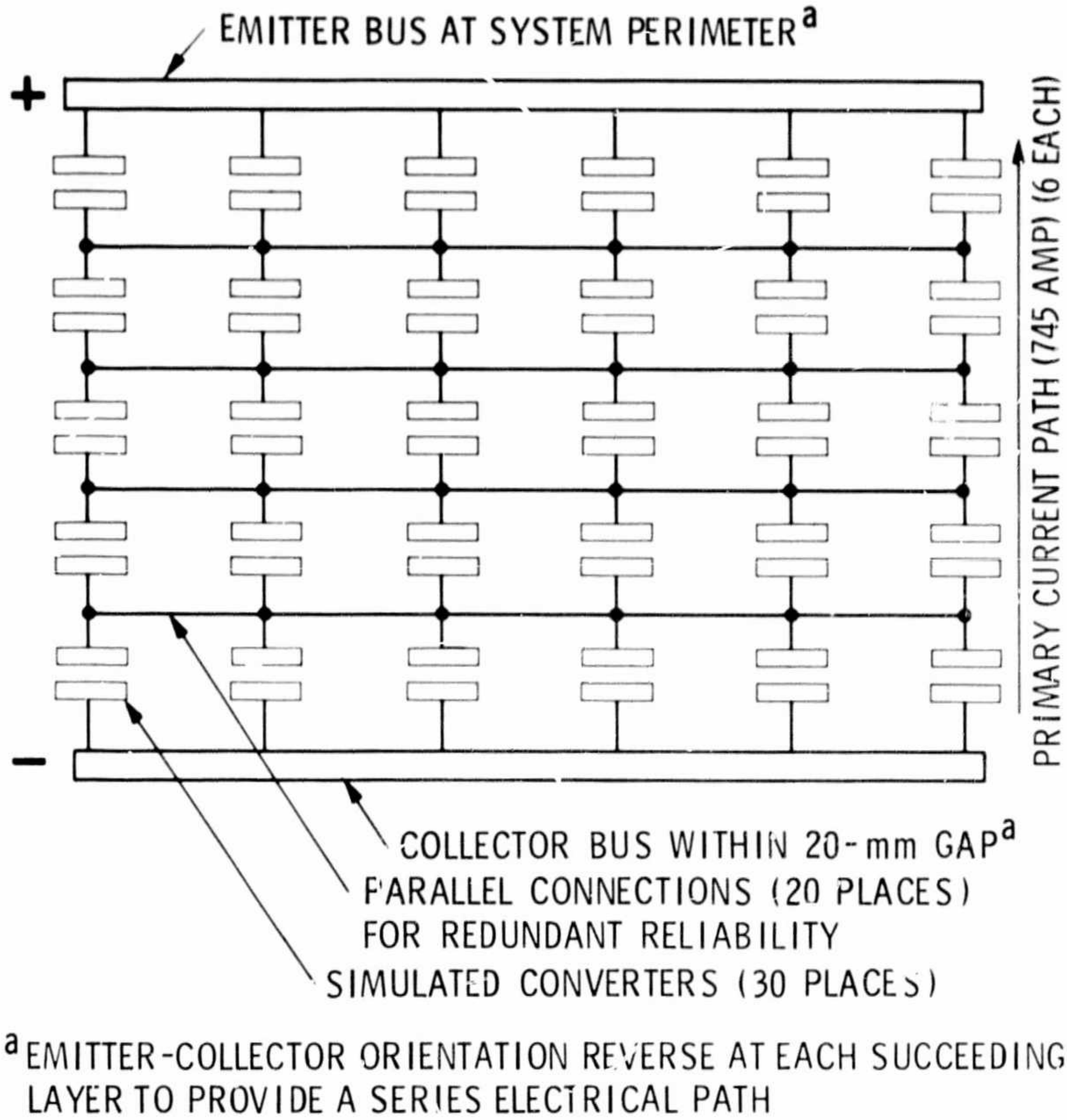

Fig. 5. Electrical connection arrangement typical for one-third of one layer

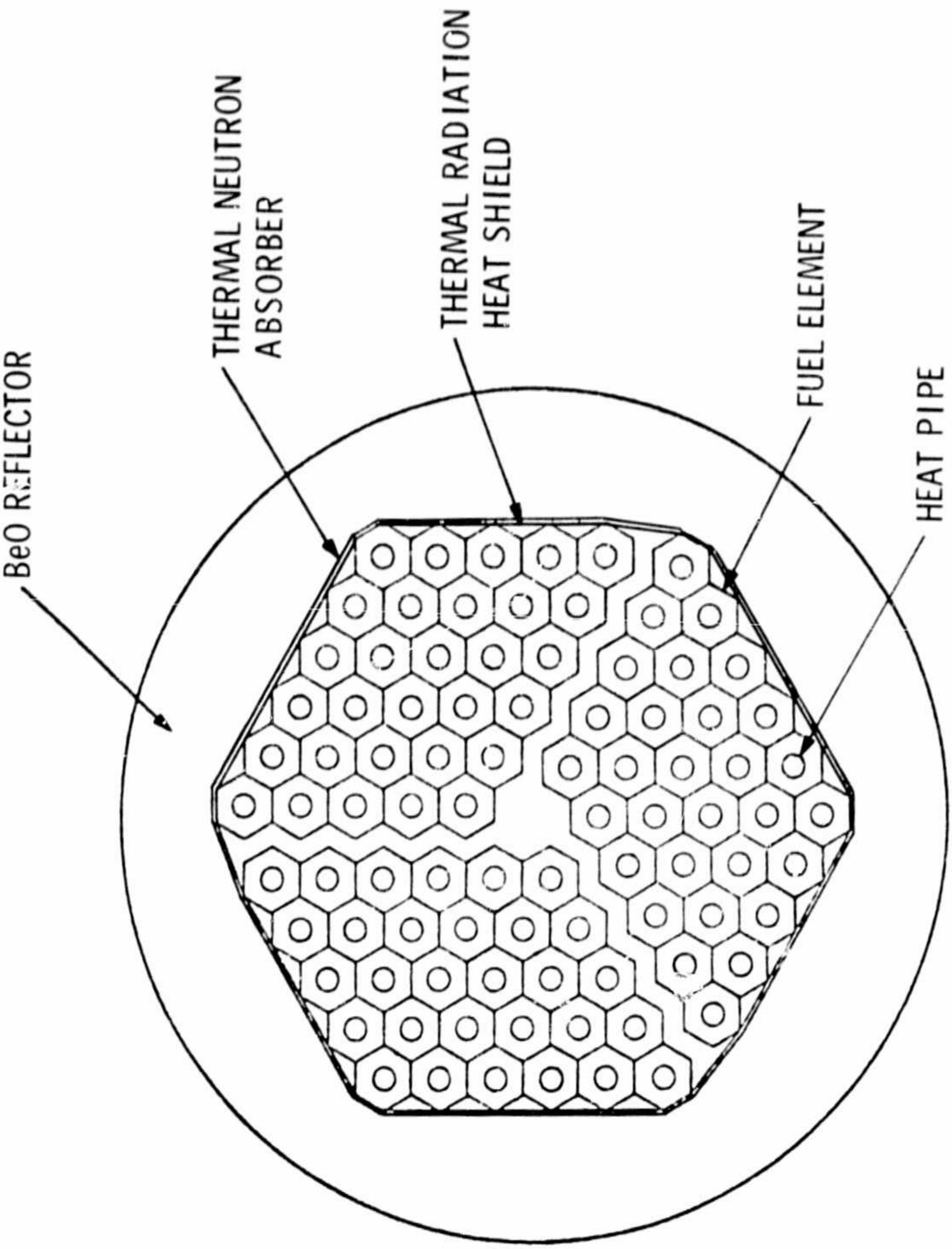

Fig. 6. Reactor cross section

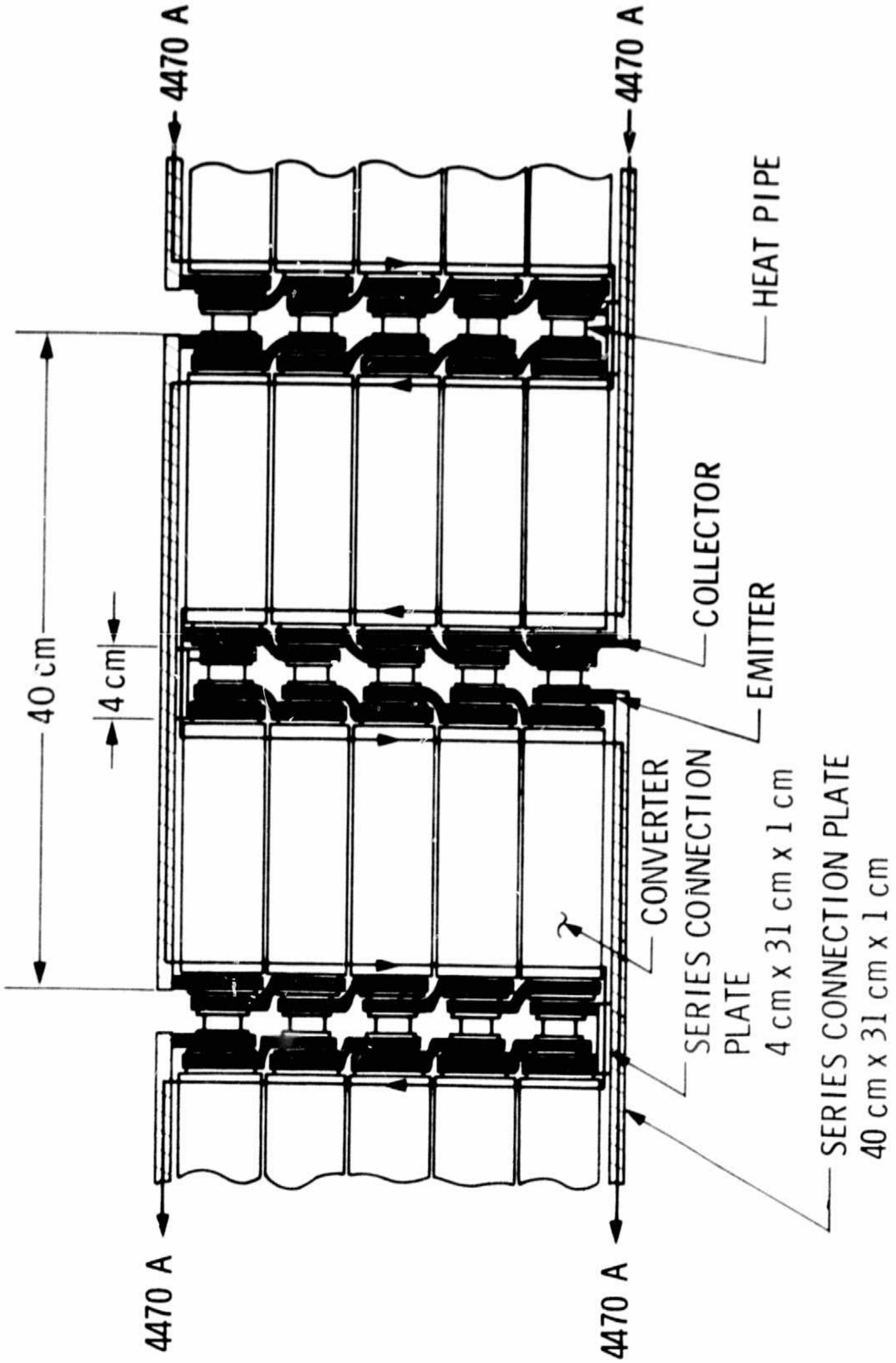

Fig. 7. Series electrical connection layout

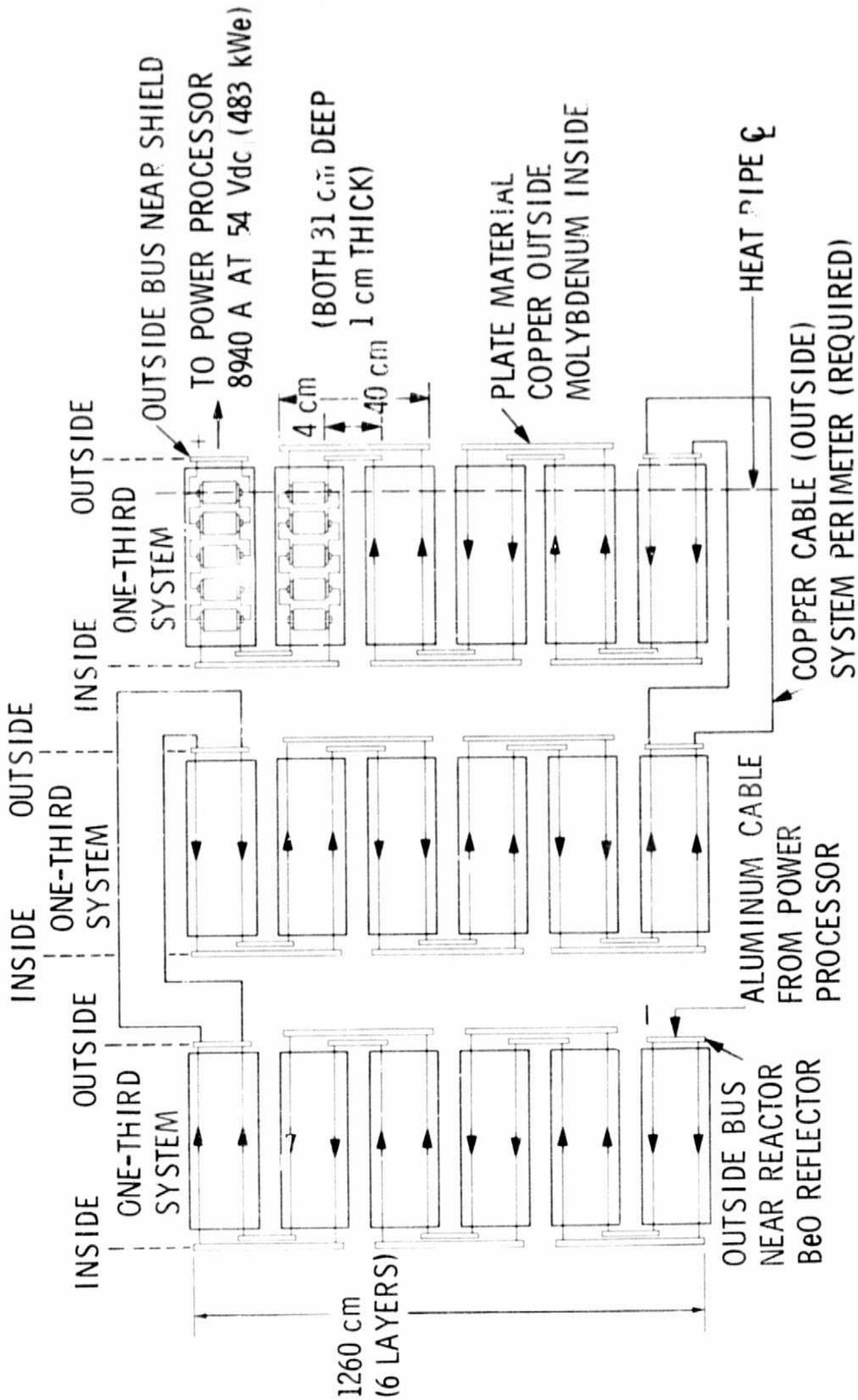

Fig. 8. Connection scheme--18 modules in series

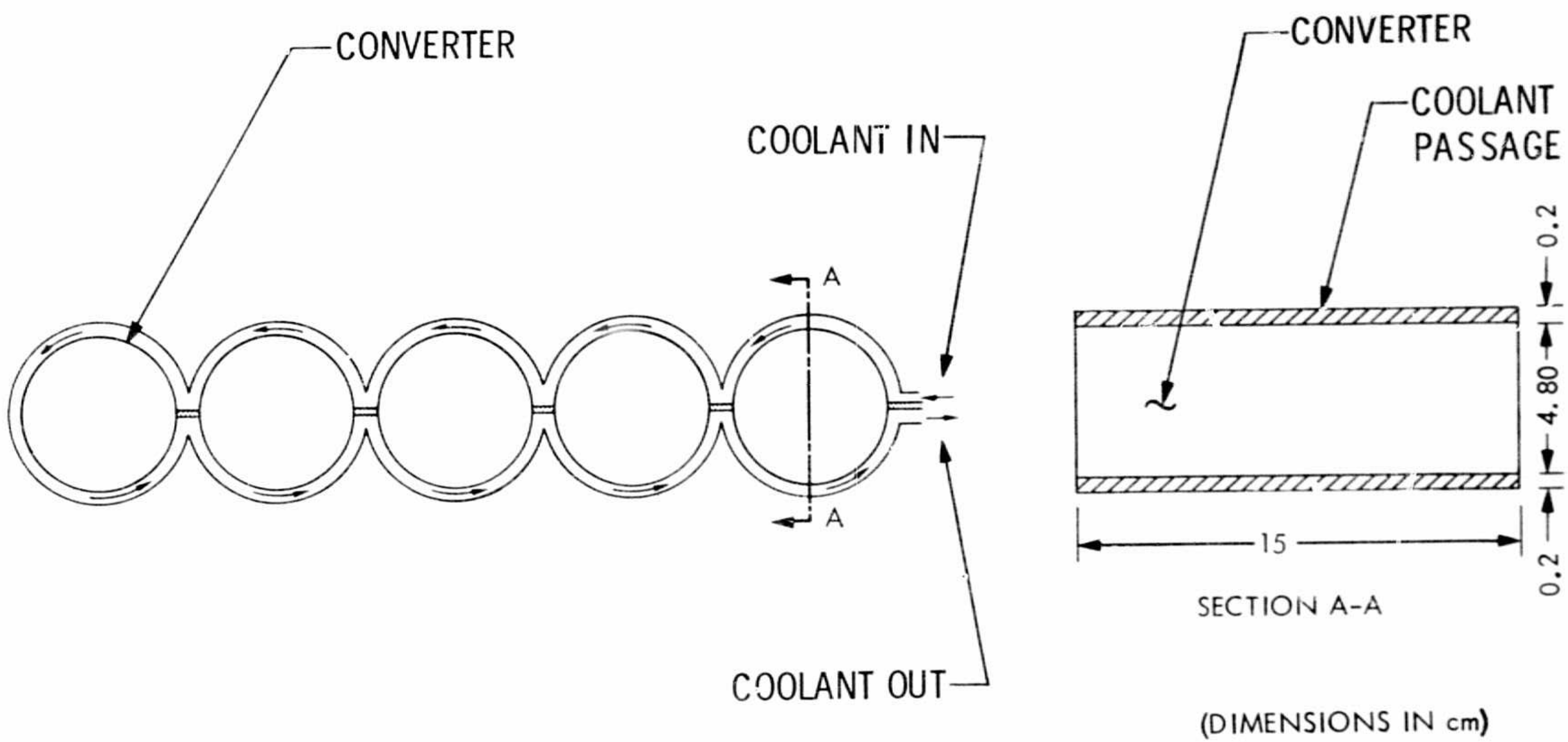

Fig. 9. Coolant channel arrangement and cross section

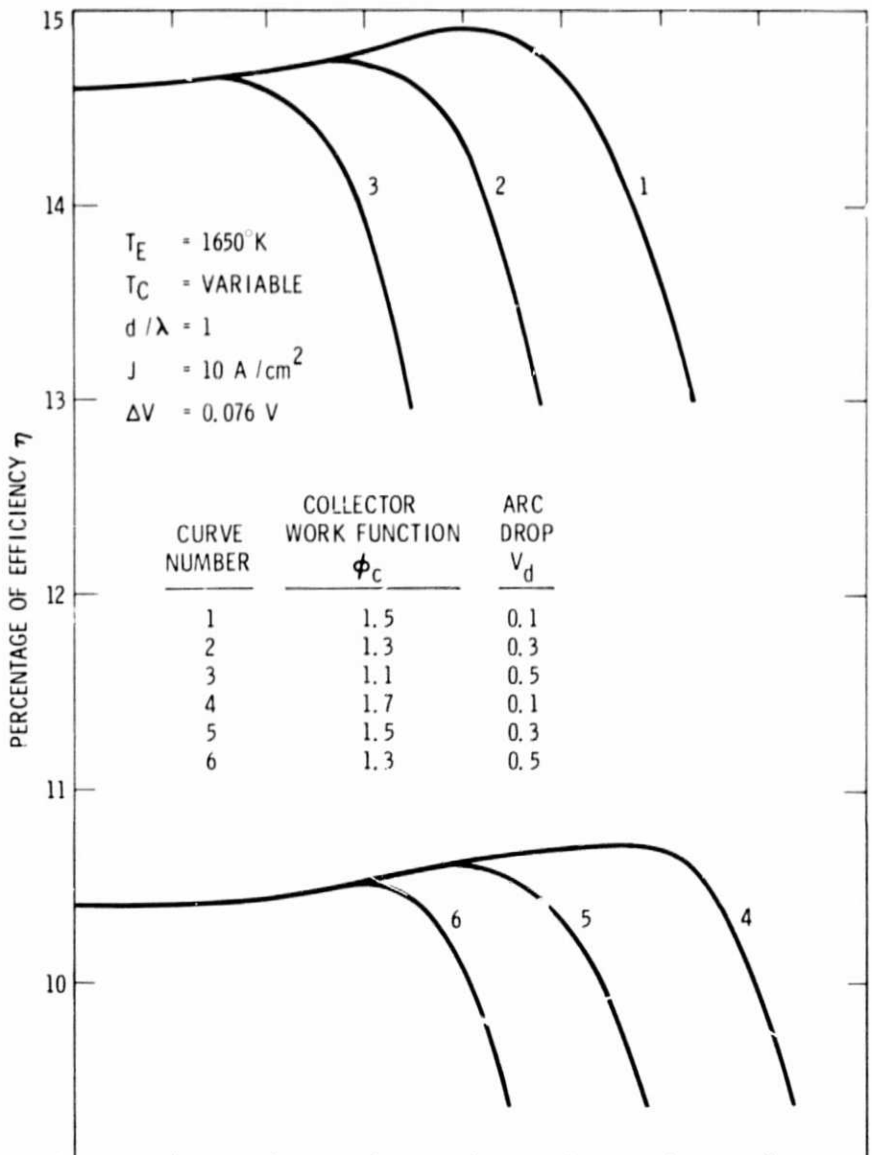

Fig. 10. System efficiency

NASA-JPL-Coml., L.A., Calif.